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REPORT

THE GENERATION OF VIDEO SYNCHRONISING PULSES AND TEST WAVEFORMS BY DIGITAL SYNTHESIS: timing errors caused by quantising distortion

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Summary

Digital waveform-synthesis produces interval timing errors, or wave-shape distortion, when generation of transitions is required at intervals which are not integer multiples of the sampling clock period. A rule has been evolved to determine the timing accuracy with which a digital system, with quantisation limitations, is capable of generating waveform transitions. Synchronising-pulse edges and 2T pulses have been generated at intervals of 1/16 of a clock-period, using a sampling clock-rate of thrice colour-sub-carrier frequency. A synchronising-pulse jitter of less than ±2·5 ns is obtainable, and tests on a video tape recorder indicate that this amount of jitter is satisfactory.

Issued under the authority of

P. Rainger

Head of Research Department

Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION

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1. Introduction

As the digital transmission and processing of video signals is further developed, there is likely to be an increasing demand for accurate and precisely-defined synchronising pulses and test waveforms, derived directly from a clock waveform at the digital sampling frequency. The generation of such signals entirely by digital methods confers the advantages of precision and repeatibility; little adjustment or setting-up is required, and any desired waveform can be produced, within the quantisation and sampling limits set by the digital parameters.

However, if the transitions within such waveforms are merely specified by a single set of samples which are generated by a simple clock-period counting technique, and the sampling frequency is not an integer multiple of line-frequency, timing errors of up to ±½ clock-period occur. These errors appear as waveform jitter* extending over the range of one clock-period.

Although the highest frequency transmitted in the video signal is usually restricted to about 5·5 MHz, the relative position of different parts of the waveform is often required to be specified to an accuracy of a few nanoseconds. Video tape recorders are particularly sensitive to jitter on synchronising pulses and recent rests have shown that some television receivers are sensitive to periodic jitter greater than ±5 ns.[1] This should be compared with the digital clock-period which, in the case of sampling at thrice colour-subcarrier frequency (≃ 13·3 MHz), is about 75 ns. Line-frequency locked sampling would, of course, eliminate the jitter problem, but in areas where composite colour signals are being processed, there are substantial reasons for adopting a sampling clock locked to thrice colour-subcarrier frequency.[2]

Digital waveform generators having a clock frequency which is not an integer multiple of line-frequency need not, however, produce timing jitter extending over one clock-period. The waveform transitions in question are normally required to be band-limited, i.e. they extend over several sampling intervals, and by an appropriate choice of the sets of numbers defining the edges (different for different lines) successive transitions can be positioned as required, subject only to quantising limitations.

This report examines the factors limiting the accuracy with which analogue waveforms of this type can be generated by digital methods, and describes tests carried out on a digitally synthesised colour-bar signal.. Emphasis was mainly directed to the case where a sampling rate of thrice colour-subcarrier frequency is used.

* The use of jitter in this Report is taken to imply systematic, discrete timing variations.

2. Waveform distortion and timing accuracy

The steepest waveform slope that can be produced by a digital system is governed by the step-function response of the analogue reconstitution filter associated with the digital-to-analogue converter (d.a.c.). The waveform appearing at the output of this filter may be regarded as the sum of a number of step-function responses occurring at clock-period intervals, with magnitudes determined by the differences (in discrete numbers of quantum levels) between successive reconstructed samples. A transient-analysis computer program[3] employs this approach, and was used to derive the analogue output waveforms obtained from a given design of analogue reconstitution filter, for various digital input signals. The shape of the output waveform is, of course, rigidly related to the sequence of digital sample values at the input to the d.a.c., and successive sets of nominally identical sample values can produce the corresponding nominally identical analogue waveforms only at discrete times separated by integer multiples of a digital clock-period. If the waveform is to repeat at any multiple of $1/n$th of a clock-period, sets of intermediate sample values must be obtained, corresponding to waveform sampling with a clock waveform delayed by multiples of $1/n$th of a clock-period. This is equivalent to using a sampling frequency n times as great, though it is clearly undesirable to increase the sampling frequency for the present purpose provided that the Nyquist criterion for the signal bandwidth has been met. Indeed, if the Nyquist criterion is satisfied, a single set of samples contains all the information required to define the waveform; the intermediate sets may be obtained by interpolation,[4] according to the impulse response of the system, as shown in Fig. 1.

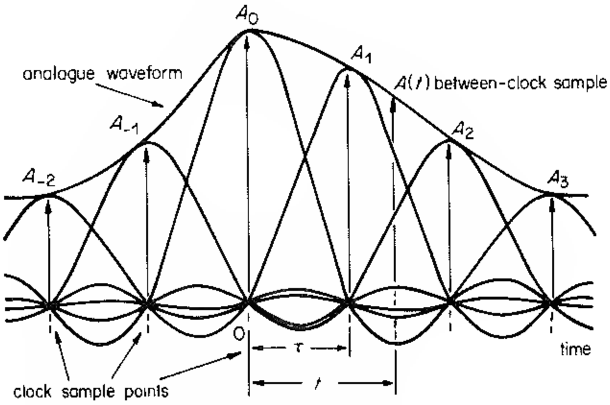


Fig. 1 - Interpolation characteristic for determination of between-clock samples

$$A(t) = \sum_{n=-\infty}^{\infty} A_n(t)\,\sin[\pi(t-n\tau)/\tau]\,/\pi(t-n\tau)$$

There is a definite limit, however, to the number of different sets of intermediate sample values that can be generated, which is set by the restrictions of amplitude quantisation. Clearly, if n is made large such that a very small time-shift is involved between successive waveform positions, the sets of sample values for adjacent positions will tend to the same set of quantum levels; thus the adjacent digitised sample sets become indistinguishable from each other. It follows that, as a general rule, it is necessary that the waveform to be synthesised has a gradient equal to, or greater than, one least significant bit* (l.s.b.) in $1/n$th of a clock-period, where n is the number of different clock sub-intervals to which the output waveform need be specified; this ensures that the n sample values within a clock-period will all be different. However, most transitions start and finish with zero gradient, and there must be some point, therefore, at which the above rule will be violated. Difficulty arises in the region between zero gradient and the gradient for which the rule is satisfied. It is inevitable that distortion will arise in these regions, and it should be ensured that such regions are not of significant interest when deciding at what point the gradient of the desired transition should satisfy the gradient rule. This is essentially a waveform 'end-effect' and will be considered later, with reference to specific waveforms.

3. Practical waveform synthesis

Before dealing with the practical generation of waveform transitions it is worthwhile to discuss briefly the analogue signal reconstitution arrangements. This is of fundamental importance since it determines the shape of the final analogue output signal corresponding to a given sequence of digitised sample values. The generation of standard and fast synchronising-pulse edges is then discussed and, in the results presented, the limitations of the d.a.c. may be observed; these results lead to an extension of the waveform gradient rule proposed above. Finally, 2T pulse generation is considered.

3.1. Analogue-signal recovery

It is important to maintain a high standard of performance in the analogue-signal reconstitution equipment used in test-waveform generation, if the basic precision of the digital circuits is not to be lost. In the present investigation, digital samples were generated and processed in 8-bit binary form, and the subsequent analogue reconstitution was provided by a prototype d.a.c.[5] and output filter.

The unfiltered output from the d.a.c. was found to deviate from the ideal 'box-car' form. Errors that affect all levels equally are not serious, but if the final level reached during any sampling period is affected by the previous sample level, asymmetrical distortions are introduced into the output. Small discrepancies of this type, occurring within the d.a.c. used in the experiments, were found to cause analogue-waveform timing-errors of up to ±1 ns.

*In digital video equipment the number of quanta describing the signal level for each sample is specified by a binary code such that one least significant bit corresponds to one quantum.

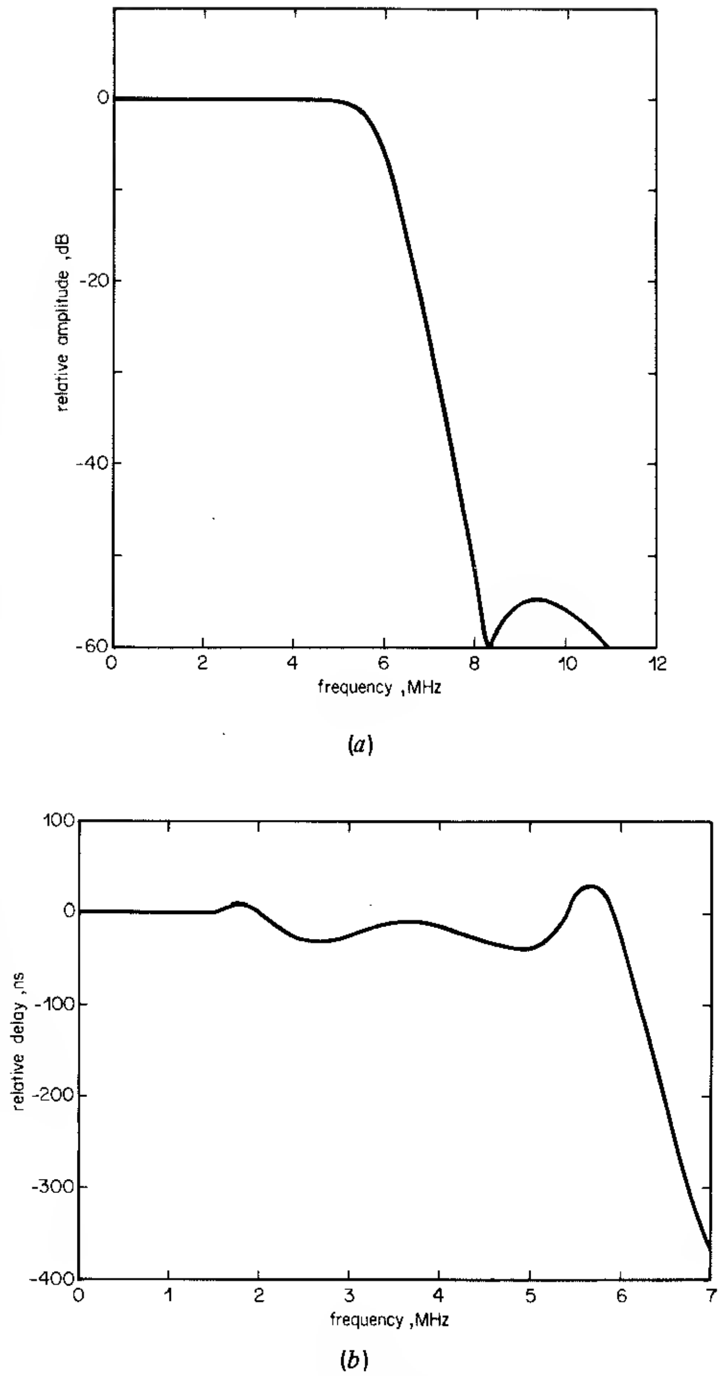
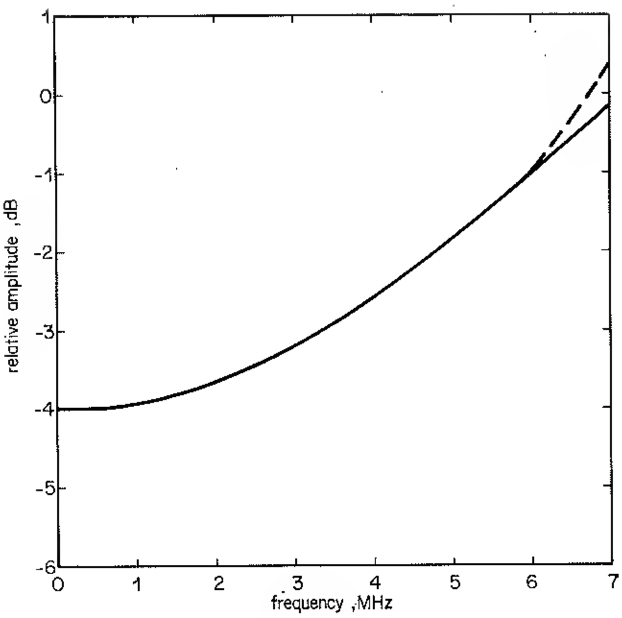


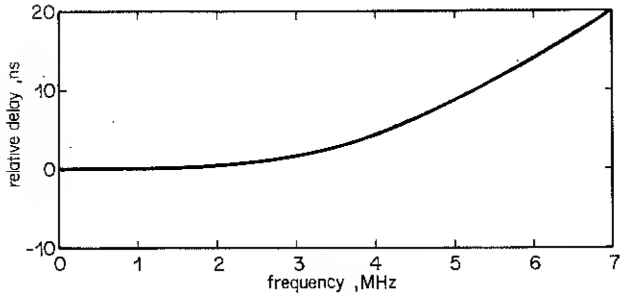
Fig. 2 - Response of video filter
(a) Amplitude-frequency plot (b) Group delay-frequency plot

A standard design of analogue 5·5 MHz video filter was used (the responses are given in Fig. 2), with a box-car equaliser at its output. The latter was of the resonant constant-resistance bridged-T form, and had an amplitude response very close to the ideal (Fig. 3(a)). The overall group-delay/frequency characteristic of the two filters (Fig. 4) was well within the specification given in Reference 6.

Thus the performance of the equipment used in the conversion from digital to analogue signals, though not perfect, was adequate for the present purposes.



(*a*)



(*b*)

Fig. 3 - Response of box-car equaliser
(*a*) Amplitude-frequency plot
-------- theory ———— measured
(*b*) Group delay-frequency plot

A useful indication of the performance of such equipment is obtained by generating a series of abrupt rising and falling edges, by initiating corresponding abrupt changes in the input digital signal. The analogue 'square-waves' formed in this manner should, if viewed on an oscilloscope triggered at twice the square-wave frequency, appear as identical wave-shapes, with corresponding rising and falling edges intersecting at the mid-points of the transitions, and be mirror-images of one another about the amplitude and time axes through this point. Fig. 5 illustrates a typical result.

3.2. The synchronising pulse

When sampling at a rate equal to thrice colour-subcarrier frequency ($\simeq$ 13·3 MHz), one television line period is equal to 851 plus 637/2500 sampling periods; thus line synchronising-pulses occur at 2500 different times within one sampling clock-period. An approximate indication of the position of such a pulse can be obtained by dividing the sampling clock-period by either 851 or 852

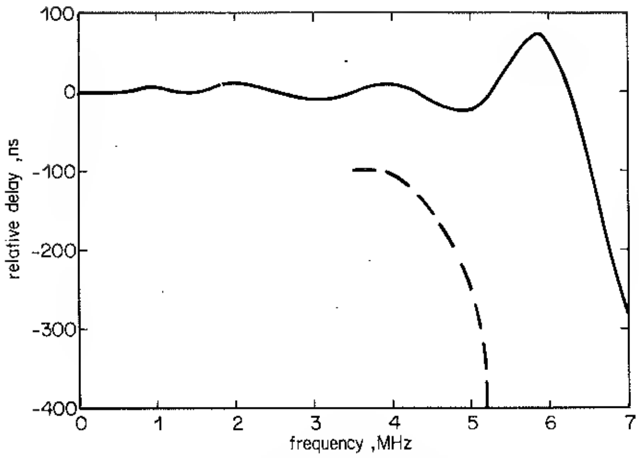


Fig. 4 - Group delay-frequency plot for complete analogue signal reconstitution filter
———— measured ------- just perceptible limit of Ref. 6

according to an 8-field sequence; the resulting pulse train has the correct average frequency but is subject to a timing jitter of peak-to-peak magnitude equal to one clock-period ($\simeq$ 75 ns).

However, the division process may be extended to generate a number representing the residual error appropriate to each line as a fraction of a clock-period, and this residue function can be used to control the read-out of an appropriate set of digital sample values from a store containing the sets corresponding to all the differently timed versions of the synchronising pulse.[7]

The shape of each edge of a synchronising pulse is ideally given by the integral of a sine-squared (raised cosine) pulse of suitable polarity, with a rise-time of 250 ± 50 ns.[8] The important requirement when synthesising such pulses is that a well-defined region has constant gradient about the mid-point of each transition. In Section 1 it was stated that timing accuracies of less than ±5 ns are some-

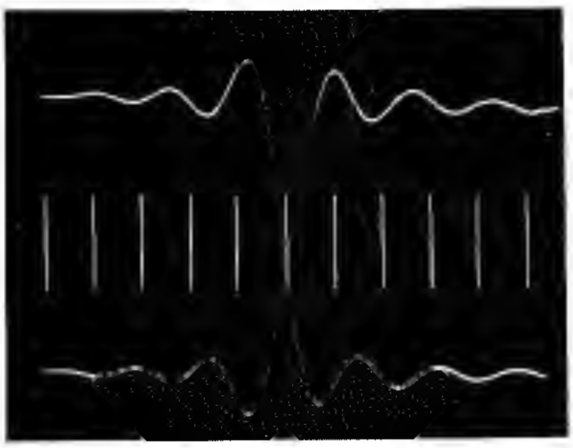


Fig. 5 - Response of analogue signal reconstitution equipment to rising and falling step-functions (time scale 100 ns/div)

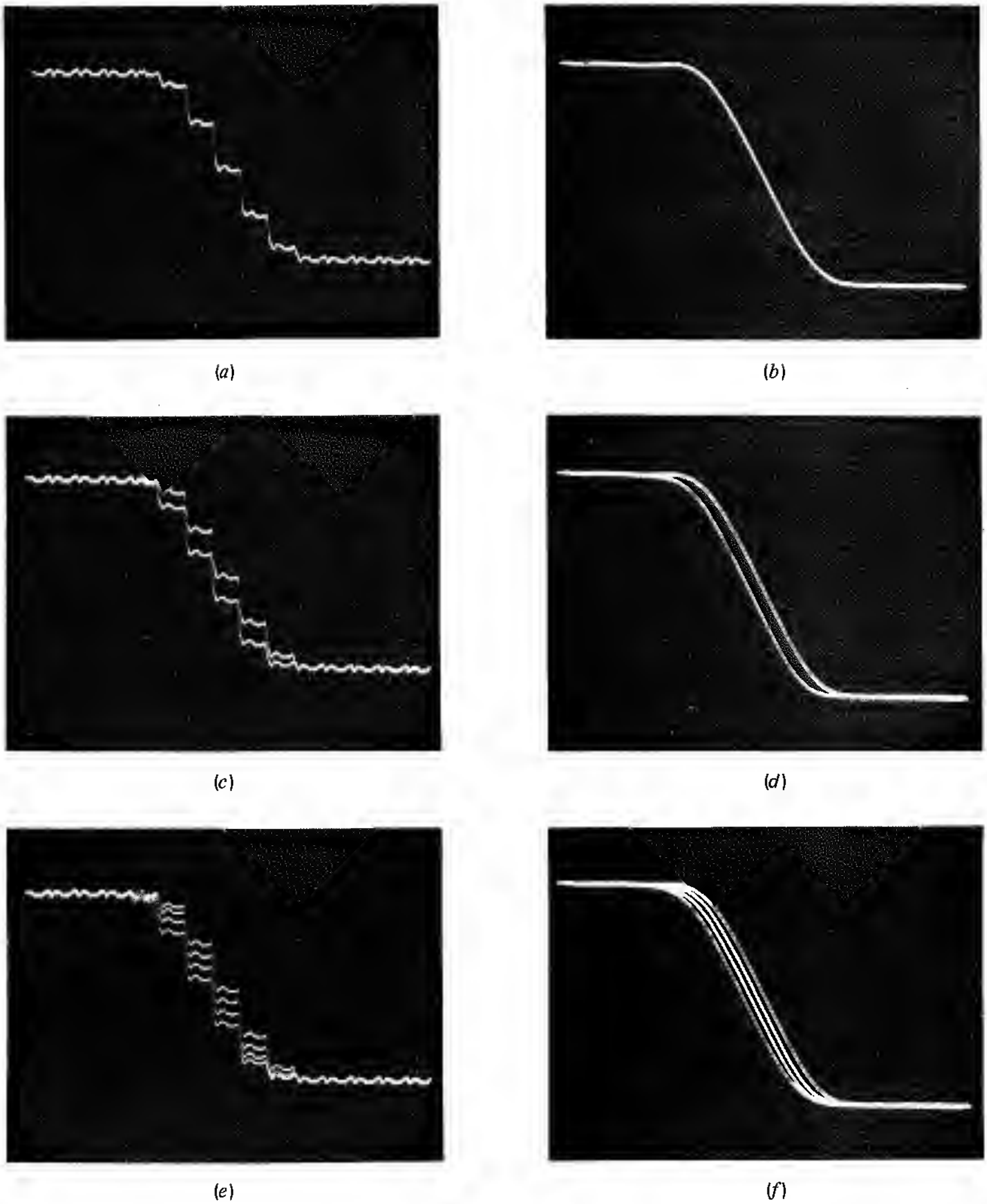
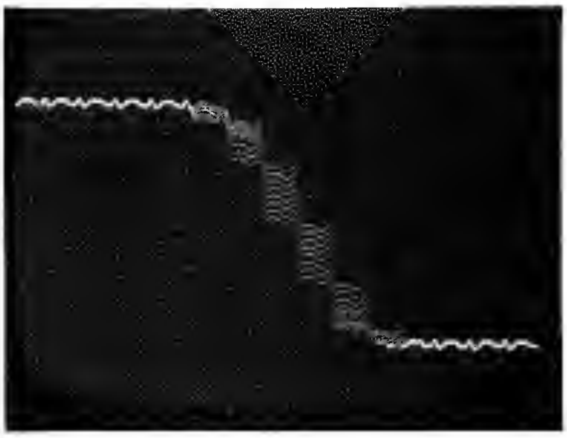
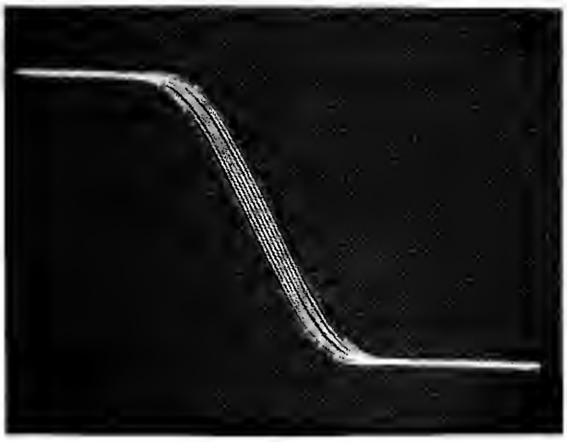


Fig. 6 - Digitally generated standard synchronising pulse edges (time scale 100 ns/div except where stated)
(*a*) and (*b*) reference quantised and filtered edge
(*c*) and (*d*) 2 edges, quantised and filtered, one delayed by $^1/_2$ clock period from the original
(*e*) and (*f*) 4 edges, quantised and filtered, each successively delayed by $^1/_4$ clock period

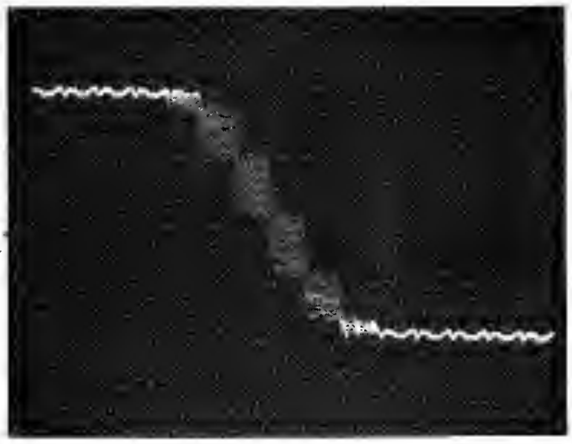
times required, and the digitised values of a synchronising-pulse edge were therefore computed to 8, 7 and 6-bit accuracy at intervals of 1/32 of a clock-period; the latter represents a time shift of approximately 2·35 ns between samples. Both the constants defining the synchronising-pulse edges and the quantised analogue samples were computed. In the latter case the values were tabulated and plotted on a line-printer to represent the waveform sampled



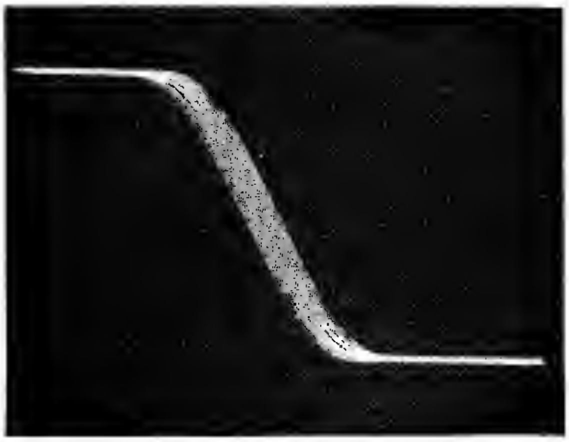
(*g*)



(*h*)



(*j*)



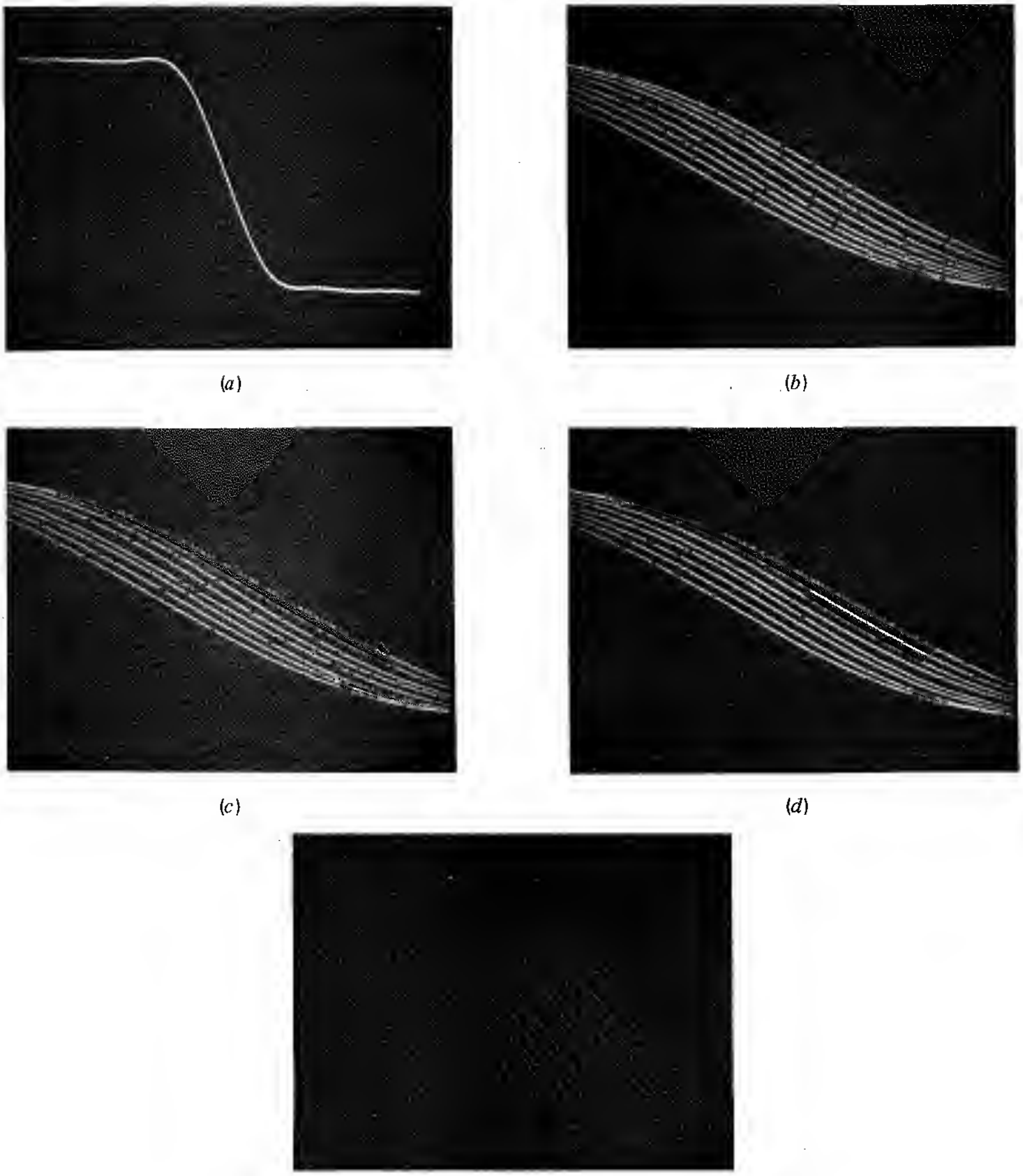
(*k*)

(*l*)

Fig. 6 - Digitally generated standard synchronising pulse edges (time scale 100 ns/div except where stated)
(*g*) and (*h*) 8 edges, quantised and filtered, each successively delayed by $^1/8$ clock period
(*j*) and (*k*) 16 edges, quantised and filtered, each successively delayed by $^1/16$ clock period
(*l*) expanded section of (*k*) about mid-point (amplitude scale x 5, time scale 10 ns/div)

at 32 times clock rate; each sample set could then be selected by taking every 32nd value.

A synchronising-pulse edge with a rise-time of 250 ns occupies about six clock-periods and the gradient is approximately constant for just over 1½ clock-periods on either side of the mid-point. This gradient corresponds to 7/4 least significant bits (l.s.b.) per clock sub-interval (1/32nd



(*a*) (*b*) (*c*) (*d*) (*e*)

Fig. 7 - Digitally generated integral 2T pulse (time scale 20 ns/div except where stated)

(*a*) filtered edge (time scale 100 ns/div) (*b*) 'A' set of 8 filtered edges spaced at approximately 9 ns intervals
(*c*) 'B' set of filtered edges shifted by approximately +3 ns from 'A' set
(*d*) 'C' set of 8 filtered edges shifted by approximately −3 ns from 'A' set
(*e*) expanded section about mid-points of 'A', 'B' and 'C' sets superimposed (amplitude scale x 5, time scale 10 ns/div)

of a clock period) with 8-bit quantisation, reducing to ½ l.s.b. per clock sub-interval with 6-bit accuracy. Thus, in the latter case, the gradient rule is not satisfied; the gradient only increases by one l.s.b. every alternate sub-interval, and therefore only 16 different evenly spaced transitions can be produced per clock-period, these being

separated by 4·7 ns intervals.

Now when 8 bits are used to code the complete television waveform, blanking and black level are positioned at about level 63, and the synchronising pulses are therefore only quantised to 6 bits accuracy. Thus the accuracy with which synchronising-pulse timing can be defined is limited to ±2·35 ns.

The experimental equipment (described in Appendix 1) was designed and built to synthesise these synchronising-pulse waveforms. It is capable of producing 16 differently-timed versions of a given pulse edge, and the digital sample values stored are shown in Appendix 2.

Fig. 6(*a*) shows the quantised version of the falling edge of the synchronising pulse corresponding to one set of values, and Fig. 6(*b*) shows the corresponding filtered analogue signal; the rise-time was measured as 260 ns. In Figs. 6(*c*) to 6(*k*) inclusive, intermediate edges corresponding to time shifts of (respectively) 1/2, 1/4, 1/8 and 1/16 of a clock-pulse period are also shown. The mid-point region of Fig. 6(*k*) is expanded in Fig. 6(*l*) to show the 16 parallel, equi-spaced edges at 4·7 ns intervals. Although the edges are parallel and equally spaced around the mid-point region, Fig. 6(*k*) confirms that this is no longer the case where the gradient tends to zero; the gradient rule is no longer satisfied and there is some overlapping of waveforms.

Sometimes a shorter rise-time, e.g. of about 200 ns, is required, particularly for transmission over long and poor links, so that the characteristics of the subsequent signal chain result in the final signal having an approximately correct rise-time. The integral of the 2T pulse provides a suitable transition with a rise-time of 200 ns,[9] and was included in the investigation. Pulse edges of this form occupy only about four clock-periods, and the constant-gradient regions extends for little more than half one clock-period either side of the mid-point of the transition. With 8-bit quantising accuracy, the gradient in this region is 3 l.s.b./clock sub-interval (32 sub-intervals/clock-period), becoming 3/4 l.s.b./clock sub-interval with 6-bit accuracy. As in the previous case, the gradient rule is again not satisfied with 6-bit accuracy, although there is a region of constant slope (24 l.s.b./clock-period) which extends over a clock-period about the mid-point. This implies that 24 equi-spaced waveforms could be synthesised at intervals of about 3 ns. In order to synthesise only 16 equi-spaced waveforms within a clock-period, using 6-bit quantisation, a gradient of 3/2 l.s.b./clock sub-interval is required. The difference in level between the samples at adjacent clock sub-intervals must, of course, be an integer, and therefore 16 equi-spaced waveforms with the required slope cannot be thus synthesised. However, 16 may be selected from the equi-spaced set of 24, and these will have mid-point timing-differences of 3 ns and 6 ns alternately.

The equipment was also used to generate the 24 pulse-edges with 200 ns rise-time. Because of storage limitations, they were produced as three sets of 8, the members of each set being spaced at 9·4 ns (see Appendix 2). Fig. 7(*a*) shows a typical integrated 2T pulse after filtering, and Figs. 7(*b*) to 7(*d*) show the three sets of 8 equi-spaced waveforms. In Fig. 7(*e*) the 3 sets are superimposed and expanded about the mid-point to show the 24 possible edges. It will be seen that they are not perfectly parallel and their separation is not constant even at the mid-point. This is due to quantisation distortion near the ends of the transition; the effect is more apparent here because the waveforms extend over only 4 clock-periods.

3.3. The waveform-gradient rule

The gradient rule evolved in Section 2 may now be extended to take account of the quantisation distortion at the ends of the transition. In order to synthesise a waveform repeatable at intervals of $1/n$th of a sampling clock-period (where n is an integer) the lowest slope to be reproduced accurately should present a gradient of m l.s.b. (where m is an integer) in $1/n$th of the sampling clock-period (1 clock sub-interval), and be maintained for more than one clock-period.

3.4. The 2T pulse

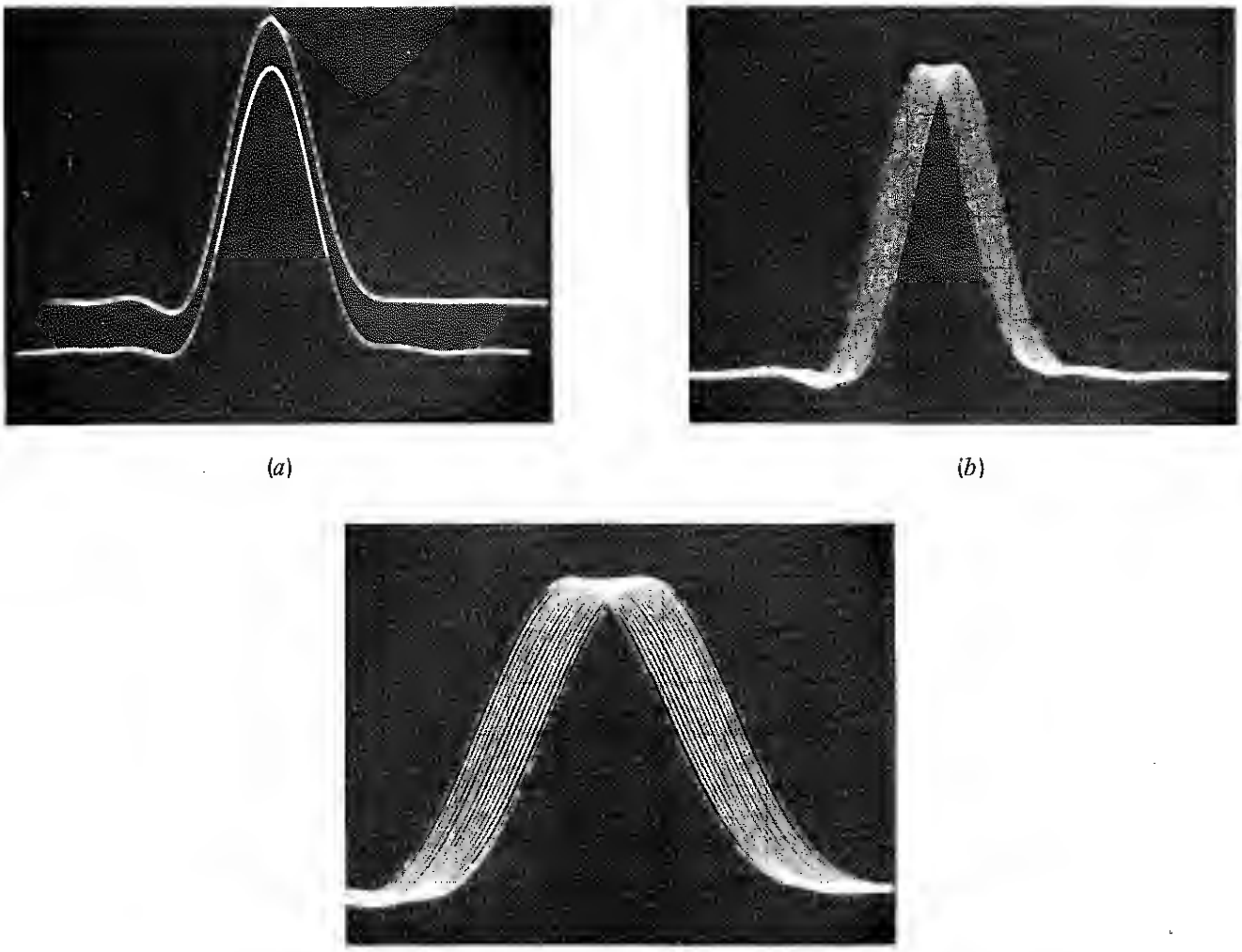
The 2T pulse is a commonly required test waveform[9] which must be generated with high accuracy since it is required for measurements of waveform distortion. The oscilloscopes used in such measurements are normally triggered by line synchronising-pulses, and line-to-line jitter is therefore acceptable so long as the 2T pulse and the synchronising pulses are equally affected. What is more important is that the shape of the 2T pulse should be consistent from line to line. The digital sample values were computed, and the equipment was programmed to give 16 equi-spaced 2T pulses at intervals of 4·7 ns, quantised to 7 bit accuracy, i.e. with 128 levels (see Appendix 2). 2T pulses within an 8-bit television insertion test-signal would normally occupy about 145 levels, and thus the results presented here may not be quite as good as those that would be obtained using the latter number of quantising levels.

Fig. 8(*a*) compares a digitally synthesised 2T pulse with that provided by an analogue test-signal generator. Fig. 8(*b*) shows 16 such waveforms displaced by equal intervals through one clock-period, and a time expanded view shows the individual waveforms more clearly around their main peaks (Fig. 8(*c*)). Note the consistency in the wave-shape; a slight variation in peak magnitude is apparent, but this would not significantly affect the measurement of k-rating.

1T pulses could be synthesised by similar methods, but a higher sampling frequency would have to be used to satisfy the Nyquist criterion. (The spectrum of the 1T pulse occupies 10 MHz to the first null.)

4. Video tape recorder test

In certain circumstances, a video tape recorder (v.t.r.) is perhaps the most susceptible form of studio apparatus to jittering synchronising pulses. A series of tests was therefore carried out using an Ampex 2000B machine to determine its susceptibility to the timing jitter of synchronising pulses digitally synthesised from a thrice colour-subcarrier



(a) (b)

(c)

Fig. 8 - Digitally generated 2T pulse (time scale 100 ns/div)
(a) filtered pulse (lower) compared with analogue generated pulse (upper)
(b) 16 filtered edges, each successively delayed by 1/16 clock period
(c) time expanded version of (b) (time scale 50 ns/div)

sampling clock, and to test the assertion that a timing accuracy of 1/16th of a clock period would be adequate.

A digitally synthesised 100% colour-bar test-waveform was generated with synchronising pulses having a residual jitter within the range $\pm 1/2^n$ ($n = 1 \rightarrow 5$) of a sampling clock period (i.e. $75/2^n$ nanoseconds). There was, of course, no jitter in the colour-burst or in the signal occurring during the active-line (picture-signal), since these were generated directly from the sampling clock running at thrice colour-subcarrier frequency. This signal was recorded in the usual way and, when replayed, passed through the AMTEC and COLORTEC signal re-timing equipment. AMTEC removes the bulk of the mechanical timing errors by substantially correcting the timing of the leading edges of the line-synchronising pulses. This, in the present instance, has the effect of transferring the synchronising-pulse jitter onto the colour-burst and the picture-signal, causing jitter of up to 120° of colour subcarrier phase. COLORTEC is designed to remove small timing errors in the burst and picture-signals, and these would not normally be very large after the removal of major timing errors by AMTEC. In the present case, however, the timing errors transferred to the signals by AMTEC were sometimes too large for COLORTEC to accommodate. This was apparent for peak values of jitter greater than ±10 ns, for which the COLORTEC correction signal was seen to exceed the normally permitted excursion, and the output picture was broken up by horizontal striations of colour error. For jitter within ±5 ns the output picture was not noticeably impaired, and the COLORTEC correction signal was of reasonable magnitude.

With the COLORTEC equipment operating within range, the v.t.r. output signal showed no evidence of jitter. It appears therefore, that an accuracy of 1/16th of a clock-period, i.e. ±2·5 ns, is entirely satisfactory, since it provides a margin for COLORTEC to correct machine errors (it is also the tolerance quoted on the COLORTEC output).

5. Conclusions

Synchronising pulses and a variety of test signals can be generated with a high degree of precision by digital

methods, and the frequency of the sampling clock need not be a multiple of line frequency. The magnitude of the line-to-line positional error depends on the number of quantising levels employed; the relationship between these two quantities has been specified in terms of a 'waveform-gradient rule'. Digital waveform-sample values have been calculated and experiments have confirmed that a line-to-line jitter within ±2·5 ns is acceptable; furthermore, synchronising and test signals (with the exception of the 1T pulse) can be generated to this accuracy, with good line-to-line consistency, within the quantisation limits imposed by an 8-bit digital television system using a thrice colour-sub-carrier sampling frequency.

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Appendix 1

Pin Matrix Digital Waveform Generator

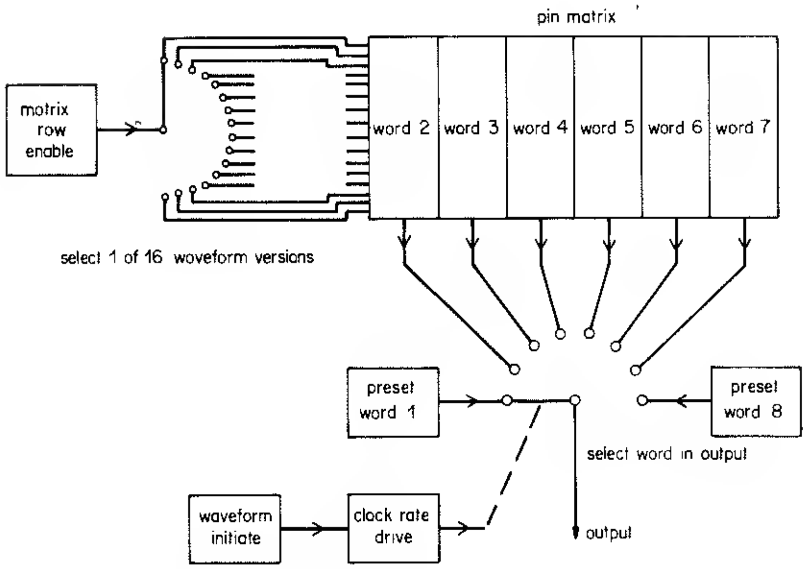


Fig. 9 - Block diagram of pin matrix waveform generator

The basis of one form of equipment capable of producing waveforms of the type discussed in this report is a digital store containing all the samples required to synthesise a waveform, or its unique parts, in as many clock sub-intervals as desired, together with suitable addressing circuits to obtain sets of digital sample values as required. Single chip 32 x 8-bit read-only memories provide an ideal storage facility, and are available in consumer programmable form. Once programmed, however, they cannot be altered and, in the experimental unit, a pin-matrix store was used, giving more flexibility.

The store was organised to give access to any one of 16 sets of six 8-bit words, each set describing one of the 16 versions of the stored waveform over six clock-periods. Read-out was in fact arranged to give a sequence of eight words, the first and last being pre-set 'end-samples' common to all sixteen waveforms. A block diagram of the equipment is shown in Fig. 9.

With no pins in the matrix the output is zero, and when the appropriate address line is connected to level '1', pins inserted in that line change the respective bits in the output words to '1's. The output is then created by reading the matrix in 8-bit parallel form, scanning it at sample rate. The sequence is started by an 'initiate' signal, and alternates in direction to produce an output corresponding to a given waveform following one initiate signal, and an output corresponding to its mirror image following the next.

Initially, the equipment was used to generate waveforms displaced with repsect to each other (e.g. those shown in Fig. 6), in order to determine the limitations of such processes. Internal timing then produced a waveform and its image at fixed intervals, sequentially derived from 1, 2, 4, 8 or 16 address lines, depending on the clock-phasing required between versions of the waveform.

Subsequently, a source of digitally generated pulses giving the approximate timing of television synchronising-pulses was made available, with line-synchronising pulses occurring every 851 or 852 clock-pulses, together with a 4-bit residue specifying the timing error to an accuracy of 1/16 of a clock-period. The equipment was then extended to accept external initiate signals (in this instance 't.t.l.' synchronising pulses), and external matrix addressing (given by the residue or its inverse).

Full details of the equipment are contained in a handbook, and only the pin-charts for the waveforms discussed in this report are included here (see Appendix 2).

Appendix 2

Pin-charts for digitally synthesised waveforms

Word 1	
'1'	X
'0'	

Matrix row	Word 2								Word 3							
Bit	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
1			X	X	X	X					X	X				
2			X	X	X	X					X	X				X
3			X	X	X	X		X			X	X			X	
4			X	X	X	X		X			X	X			X	X
5			X	X	X	X		X			X	X		X		
6			X	X	X	X	X				X	X		X		X
7			X	X	X	X	X				X	X		X	X	
8			X	X	X	X	X				X	X		X	X	X
9			X	X	X	X	X	X			X	X		X	X	X
10			X	X	X	X	X	X			X	X	X			
11			X	X	X	X	X	X			X	X	X			X
12			X	X	X	X	X	X			X	X	X			X
13			X	X	X	X	X	X			X	X	X		X	
14			X	X	X	X	X	X			X	X	X		X	
15			X	X	X	X	X	X			X	X	X		X	X
16			X	X	X	X	X	X			X	X	X		X	X

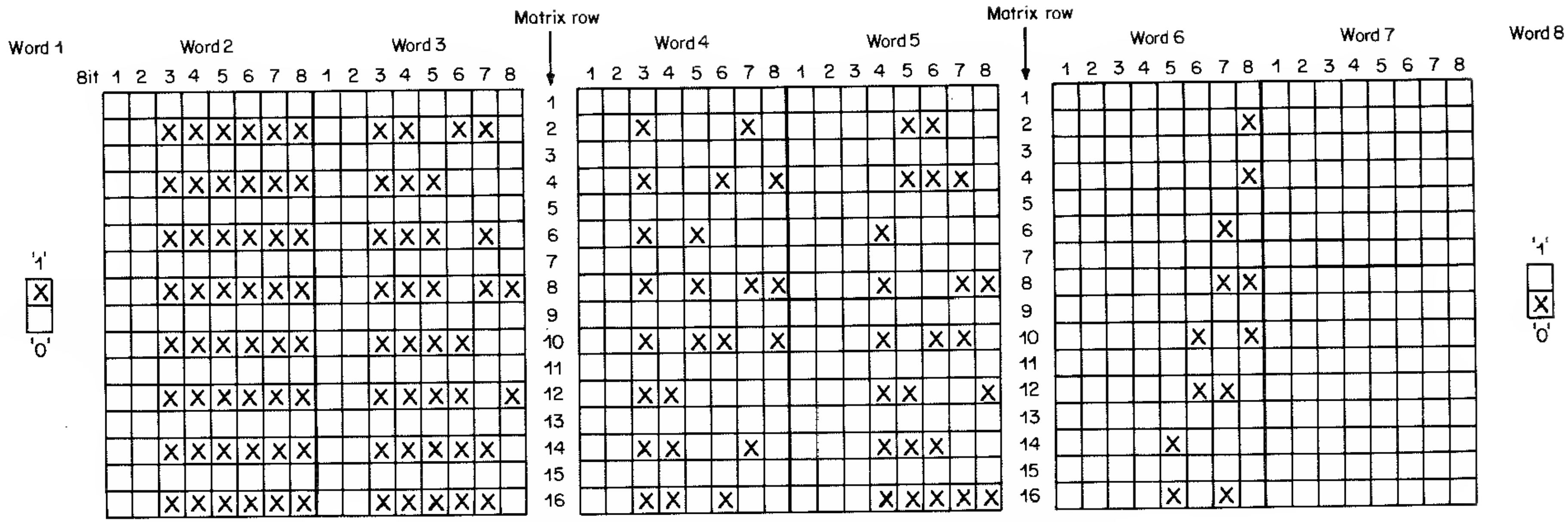
Matrix row	Word 4								Word 5							
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
1			X									X				
2			X					X				X				X
3			X				X					X			X	
4			X				X	X				X			X	X
5			X			X						X		X		
6			X			X		X				X		X		X
7			X			X	X					X		X	X	
8			X			X	X	X				X		X	X	X
9			X		X							X	X			
10			X		X			X				X	X			X
11			X		X		X					X	X		X	
12			X		X		X	X				X	X		X	X
13			X		X	X						X	X	X		
14			X		X	X		X				X	X	X		X
15			X		X	X	X					X	X	X	X	
16			X		X	X	X	X				X	X	X	X	X

Matrix row	Word 6								Word 7							
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
1						X										
2						X		X								
3						X		X								
4						X	X									X
5						X	X									X
6						X	X	X								X
7						X	X	X								X
8					X											X
9					X			X							X	
10					X			X							X	
11					X		X								X	
12					X		X	X							X	
13					X	X									X	X
14					X	X		X							X	X
15					X	X	X								X	X
16					X	X	X	X						X		

Word 8	
'1'	
'0'	X

'x' indicates inserted pin, producing '1' in appropriate bit of output waveform

(a) standard synchronising pulse edge (6-bit accuracy)



'x' indicates inserted pin, producing '1' in appropriate bit of output waveform

(b) integral 2T pulse, set 'A' (6-bit accuracy)

Word 1: '1' X, '0' (blank)

Matrix row	Word 2								Word 3							
Bit	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
1																
2			X	X	X	X	X	X			X	X		X		X
3																
4			X	X	X	X	X	X			X	X		X	X	X
5																
6			X	X	X	X	X	X			X	X	X			X
7																
8			X	X	X	X	X	X			X	X	X		X	X
9																
10			X	X	X	X	X	X			X	X	X	X		
11																
12			X	X	X	X	X	X			X	X	X	X		X
13																
14			X	X	X	X	X	X			X	X	X	X	X	
15																
16			X	X	X	X	X	X			X	X	X	X	X	

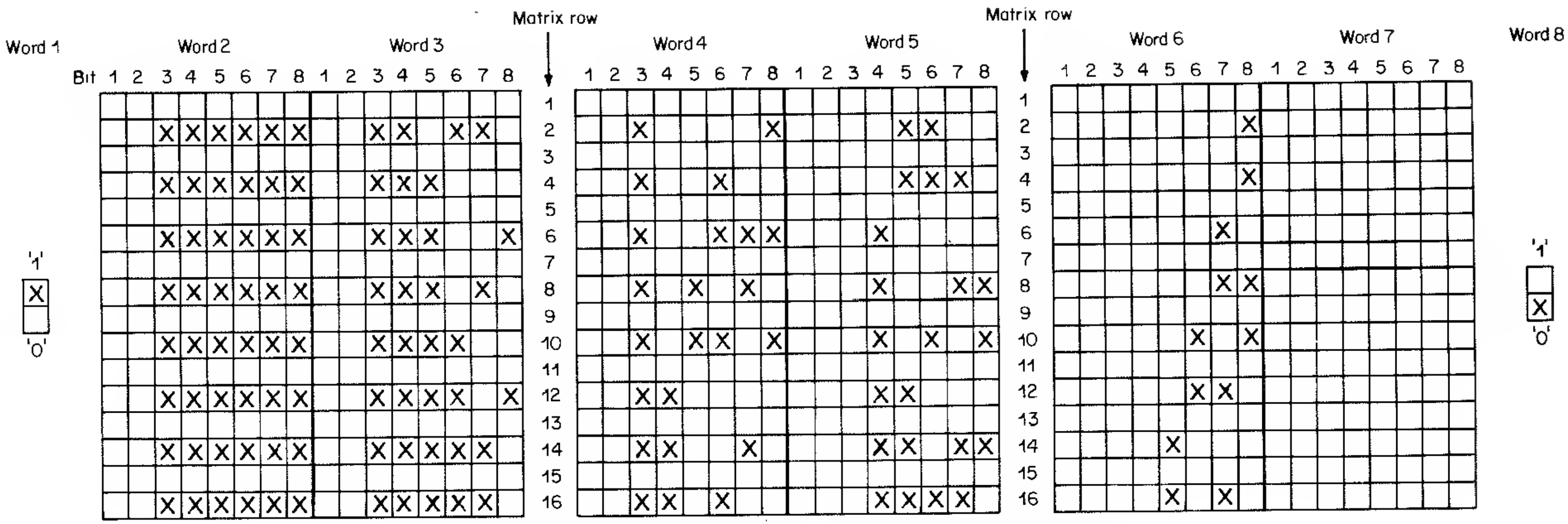
Matrix row	Word 4								Word 5							
Bit	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
1																
2			X										X		X	X
3																
4			X				X	X					X	X		X
5																
6			X			X	X						X	X	X	X
7																
8			X		X			X				X			X	
9																
10			X		X	X						X		X		
11																
12			X		X	X	X	X				X		X	X	X
13																
14			X	X				X				X	X		X	
15																
16			X	X			X	X				X	X	X		X

Matrix row	Word 6								Word 7							
Bit	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
1																
2								X								
3																
4								X								
5																
6							X									
7																
8							X	X								
9																
10						X										
11																
12						X		X								
13																
14						X	X	X								
15																
16					X			X								

Word 8: '1' (blank), '0' X

'X' indicates inserted pin, producing '1' in appropriate bit of output waveform

(c) integral 2T pulse, set 'B' (+3 ns shift from set 'A')



'x' indicates inserted pin, producing '1' in appropriate bit of output waveform

(d) integral 2T pulse, set 'C' (–3 ns shift from set 'A')

Word 1

'1'

'0'

Matrix row	Word 2 Bit 1	2	3	4	5	6	7	8	Word 3 Bit 1	2	3	4	5	6	7	8
1				X						X		X		X		X
2					X	X		X		X		X				X
3					X		X			X			X	X		
4					X					X				X	X	X
5						X	X			X					X	X
6						X					X	X	X	X	X	
7							X				X	X	X			X
8								X			X	X		X		X
9											X	X				
10											X		X		X	X
11											X			X	X	X
12											X				X	X
13												X	X	X	X	X
14												X	X		X	X
15												X		X	X	X
16												X			X	X

Matrix row	Word 4 Bit 1	2	3	4	5	6	7	8	Word 5 Bit 1	2	3	4	5	6	7	8
1		X	X	X	X	X	X	X		X		X	X		X	
2		X	X	X	X	X	X	X		X		X	X	X	X	
3		X	X	X	X	X	X			X	X				X	
4		X	X	X	X	X		X		X	X			X	X	
5		X	X	X	X		X	X		X	X		X		X	
6		X	X	X	X		X			X	X		X	X		X
7		X	X	X	X					X	X	X				
8		X	X	X		X	X			X	X	X			X	X
9		X	X	X			X	X		X	X	X		X	X	
10		X	X	X						X	X	X	X			
11		X	X		X	X		X		X	X	X	X		X	
12		X	X		X			X		X	X	X	X	X		
13		X	X			X	X			X	X	X	X	X		X
14		X	X				X			X	X	X	X	X	X	
15		X		X	X	X	X			X	X	X	X	X	X	X
16		X		X	X			X		X	X	X	X	X	X	X

Matrix row	Word 6 Bit 1	2	3	4	5	6	7	8	Word 7 Bit 1	2	3	4	5	6	7	8
1				X		X										
2				X		X	X	X								
3				X	X		X	X								
4				X	X	X	X	X								
5			X				X	X								
6			X		X											
7			X		X	X										
8			X	X				X								
9			X	X		X		X								X
10			X	X	X		X								X	
11			X	X	X	X	X							X		
12		X					X	X						X	X	
13		X			X								X			
14		X			X	X		X					X		X	X
15		X		X				X					X	X		X
16		X		X		X		X				X				

Word 8

'1'

'0'

'x' indicates inserted pin, producing '1' in appropriate bit of output waveform

(e) 2T pulse (7-bit accuracy)

Word 1

'1' X
'0'

Matrix row	Word 2 bit 1	2	3	4	5	6	7	8	Word 3 bit 1	2	3	4	5	6	7	8
1	X	X	X		X	X	X	X	X	X						
2	X	X	X	X				X	X	X				X		
3	X	X	X	X			X		X	X			X			
4	X	X	X	X		X			X	X			X	X		
5	X	X	X	X		X		X	X	X		X				
6	X	X	X	X		X	X		X	X		X		X		
7	X	X	X	X	X				X	X		X		X	X	X
8	X	X	X	X	X			X	X	X		X	X		X	
9	X	X	X	X	X		X		X	X		X	X	X		X
10	X	X	X	X	X		X	X	X	X	X					
11	X	X	X	X	X	X			X	X	X				X	
12	X	X	X	X	X	X			X	X	X			X		X
13	X	X	X	X	X	X		X	X	X	X			X	X	X
14	X	X	X	X	X	X	X		X	X	X		X			X
15	X	X	X	X	X	X	X		X	X	X		X		X	X
16	X	X	X	X	X	X	X	X	X	X	X		X	X		X

Matrix row	Word 4 bit 1	2	3	4	5	6	7	8	Word 5 bit 1	2	3	4	5	6	7	8
1	X									X						
2	X					X				X				X		
3	X				X					X			X			
4	X				X	X				X			X	X		
5	X			X						X		X				
6	X			X		X				X		X		X		
7	X			X	X					X		X	X			
8	X			X	X	X				X		X	X	X		
9	X		X							X	X					
10	X		X			X				X	X			X		
11	X		X		X					X	X		X			
12	X		X		X	X				X	X		X	X		
13	X		X	X						X	X	X				
14	X		X	X		X				X	X	X		X		
15	X		X	X	X					X	X	X	X			
16	X		X	X	X	X				X	X	X	X	X		

Matrix row	Word 6 bit 1	2	3	4	5	6	7	8	Word 7 bit 1	2	3	4	5	6	7	8
1				X												
2				X			X									X
3				X		X										X
4				X		X	X								X	
5				X	X										X	X
6				X	X		X								X	X
7				X	X	X								X		
8				X	X	X	X	X						X		X
9			X				X							X	X	
10			X			X		X						X	X	X
11			X		X								X			
12			X		X	X							X			X
13			X	X									X		X	
14			X	X		X							X		X	X
15			X	X	X								X	X		
16			X	X	X	X							X	X	X	

Word 8

'1'
'0' X

'X' indicates inserted pin, producing '1' in appropriate bit of output waveform

(f) standard synchronising pulse edge (8-bit accuracy)

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